Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation

Shweta Srinivasan [a], Nazar Kholod [b,*], Vaibhav Chaturvedi [c], Probal Pratap Ghosh [d], Ritu Mathur [e], Leon Clarke [b], Meredydd Evans [b], Mohamad Hejazi [b], Amit Kanudia [a], Poonam Nagar Koti [c], Bo Liu [b], Kirit S. Parikh [d], Mohammed Sahil Ali [a], Kabir Sharma [e]

[a] Center for Study of Science, Technology and Policy, Bangalore, India
[b] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA
[c] Council on Energy, Environment and Water, New Delhi, India
[d] Integrated Research and Action for Development, New Delhi, India
[e] The Energy and Resources Institute, New Delhi, India

HIGHLIGHTS

- Water withdrawals and consumption for electricity generation in India are analyzed.
- Five modeling teams tested several scenarios for water use through 2050.
- Effects of cooling technologies and water saving policies are analyzed.

ARTICLE INFO

ABSTRACT

This paper provides projections of water withdrawals and consumption for electricity generation in India through 2050. Based on the results from five energy-economic modeling teams, the paper explores the implications of economic growth, power plant cooling policies, and electricity CO_2 emissions reductions on water withdrawals and consumption. To understand how different modeling approaches derive different results for energy-water interactions, the five teams used harmonized assumptions regarding economic and population growth, the distribution of power plants by cooling technologies, and withdrawals and consumption intensities. The multi-model study provides robust results regarding the different but potentially complementary implications of cooling technology policies and efforts to reduce CO_2 emissions. The water implications of CO_2 emissions reductions depend critically on the approach to these reductions. Focusing on wind and solar power reduces consumption and withdrawals, a focus on nuclear power increases both, and a focus on hydroelectric power could increase consumptive losses through evaporation. Policies focused specifically on cooling water can have substantial and complementary impacts.

1. Introduction

India is one of the most water-stressed nations in the world. Fifty-four percent of India's total area faces high or extremely high water stress [1], and the country is close to being categorized as "water scarce" nation [2]. According to a World Resources Institute study, India's baseline water stress scored 3.6 out of 5.0 in 2010, which indicates a high ratio of total annual water withdrawals to total annual available renewable supply [3]. The country relies heavily on groundwater, and 54% of India's groundwater wells face falling water tables [1]. India is one of the countries with the world's highest rates of groundwater depletion [4].

Continued economic development will lead to increasing demands for water—for agriculture, electricity, industry, and households—putting pressure on local and national planners to develop long-term and forward-looking solutions. Climate change could substantially alter the timing, quantity, and location of run-off, including changes to monsoon patterns. Climate change mitigation will also alter the demands for water through, for

example, changes in the electricity mix or the production of bioenergy.

India is the fifth largest electricity producer in the world, but nearly 288 million Indians still have no access to the electricity grid [5,6]. The Indian government aims to substantially increase energy access for millions of Indians and increase the use of electricity by those who already have access. The Indian government has started the *Power for All* campaign to achieve electrification of all villages in India by the end of 2019. Projections from the International Energy Agency (IEA) indicate that India could add about 600 million new electricity consumers by 2040. That electricity demand might grow by 5% per year [7].

Expanding electricity production could exacerbate potential water scarcity. Given limits to water availability, satisfying agricultural and other needs could result in the curtailment of electric power plants and associated blackouts or brownouts. Conversely, increasing water demands for electricity could have repercussions for agriculture and households. Several regions in India are increasingly relying on pumped ground water to meet municipal and agricultural needs, as is seen in some water-scarce countries where conventional water resources are inadequate to meet demands [8,9]. A failure to plan adequately for the long term could lock in approaches to water management, agriculture, and electricity that could prove limiting for decades to come.

India declared a voluntary goal of reducing the emissions intensity of its GDP by 30–35% over 2005 levels by 2030 [10]. The power sector contributes 51% of CO_2 emissions in India [11]. Policies to "decarbonize" electricity generation could help constrain future water demands, but the effect will depend on the approach to decarbonization. On April 22, 2016, India, along with 174 member countries of the United Nations, signed the Paris Agreement to reduce greenhouse gas emissions across the globe. India ratified the Paris Agreement on October 2, and the agreement entered into force on November 4, 2016. Reducing CO_2 emissions from electricity generation is critical for achieving a reduction in emission intensity. As part of that agreement, all countries will need to make major changes in the way that they produce electricity, moving from freely emitting coal and gas generation to increased use of some combination of renewable power (such as wind, solar, and hydroelectric power), nuclear power, and coal or natural gas with carbon dioxide capture and storage (CCS). These different options will have very different implications for electricity water demands. Solar photo-voltaic (PV) and wind power for example, require no water for cooling, whereas nuclear power and coal or gas with CCS are still thermal power plants with the need for cooling water. Evaporative losses from reservoirs for hydroelectric power can be substantial.

At the same time, the challenge of growing water demand for electricity production is increasingly being realized by policy makers in India, as reflected in the Government of India (GOI) rules to minimize water consumption by inland power plants. To explore the implications of growing electricity demands, efforts to reduce electricity-sector CO_2 emissions, and power plant cooling technology regulations, this study brings together four leading Indian modeling teams and one US modeling team to explore the following questions. First, how will water withdrawals and consumption from India's power-generation sector increase in the future? Second, how would decarbonization of India's power-generation sector affect water withdrawals and consumption? Third, how would a shift towards water-saving technologies impact water withdrawal and consumption in the power sector? Finally, how might these forces interact with one another? Understanding the answers to these questions is critical because Indian decision makers are considering choices in the electricity sector that will affect their country for years to come.

A number of studies have explored these issues using individual models. Most generally, there is a growing body of literature on the energy-water nexus in various countries and at various scales, for example in the US [12–23], China [24–31], Middle East and North Africa [32], Saudi Arabia [8,33], Mexico [34], and Spain [35]. Researchers have also analyzed water availability for power generation and for various climate change mitigation options at the global scale [36–43].

While water-energy issues have been analyzed for the largest economies like the US and China, there are surprisingly few studies on the water-energy nexus in India. In the context of India's power sector, the IEA estimated water use in 2010 as 40 billion cubic meters (bcm) for withdrawal and 4 bcm for consumption, with the vast majority in each category going to electricity generation [44]. Mitra, Bhattacharya, and Zhou calculated India's water demand (withdrawals) for electricity generation in 2010 as 49 bcm [45]. Bhattacharya and Mitra estimated total water demand for electricity generation at about 227 bcm in 2050, which would create a deficit of 100 bcm per year in terms of annual water supply and demand, or about a 10% gap in the total annual utilizable water [46]. However, the uncertainty of India's water use is very high. Studies show that industry accounts for 9% of water consumption in India [2], and thermal power plants account for about 88% of the total industrial water demand in the country [47,48].

While previous studies have provided valuable contributions to the understanding of the energy-water nexus in India, the fact that they were produced by different modeling teams using different assumptions makes comparison difficult and also limits assessment of how robust the results might be.

This study builds on that previous work by using multiple models with coordinated assumptions. Multi-model studies such as this provide a means to identify areas of agreement and robust understanding as well as areas in which substantial uncertainty remains. The unique contribution of this study is that this is the first time that four Indian modeling teams and one US-based team have come together for an India-specific assessment. This assessment and the results will provide policy makers and other stakeholders with a more robust assessment of India's future needs for water for thermal power plants.

This study analyzes water withdrawals and water consumption by India's electricity-generating power plants. Following the same definitions given in the literature [49,50], "water withdrawal" is "water removed from the ground or diverted from a surface-water source," and "water consumption" is "the portion of withdrawn water not returned to the immediate water environment."

The remainder of this paper proceeds as follows. Section 2 provides a brief overview of water use for electricity in India today. Section 3 explains the methods used in the paper, including the models, the scenarios, and the common assumptions. Results are provided in Section 4, and Section 5 provides final thoughts.

2. Electricity water use in India today

The estimates of water use in India's statistics are not based on measurements of actual use but on specific assumptions for each sector [51], and there is no comprehensive database to gauge reliance of the power sector on fresh water resources. The Center for Study of Science, Technology and Policy (CSTEP) estimated that in 2010, the majority of the plants (about 84% of coal-based thermal power plants by count) in India used fresh water resources. Plant-level data from the Central Electricity Authority database for existing plants was cross-referenced with data collected on water sources. These included 48% authenticated data points [52], 36% non-authenticated sources (newspaper articles, industry

visit reports, and online research reports) and 16% data points based on assumption of 3 km proximity to seawater.

According to a World Resources Institute study, more than 70% of India's coal power plants are located in water-stressed or water-scarce areas [53]. An inadequate cooling water supply for power plants already creates problems in India's power sector. For example, the Sepat power plant in the state of Chhattisgarh, one of the ten biggest in India, was shut down in March 2008 due to a lack of cooling water. All six units of the Parli thermal power plant with an installed capacity of 1130 MW were shut down in February 2013 because of a severe water shortage in the Maharashtra region [54]. As electricity generation increases, power plants will demand more water for cooling, exacerbating potential conflicts between the use of power for electricity, agriculture, industry and households.

India operates older-generation thermal power plants with open-loop, or once-through, cooling technologies. These cooling systems have an average water use intensity of about 80–160 m^3/MW h or around 40–80 times higher than the average modern closed-loop, or recirculating, system [6]. To decrease the water use for electricity generation, India banned the construction of thermal power plants with once-through cooling technologies using fresh water in 1999 [7].

3. Methodology

3.1. Models used in the analysis

3.1.1. Center for Study of Science, Technology and Policy

CSTEP is a multi-disciplinary research institution with focuses on energy, infrastructure, security studies, materials, climate studies, and governance. CSTEP has developed the India Multi-Region TIMES (IMRT) model based on the MARKAL-EFOM suite to study the growth of the energy sector using the Integrated MARKAL-EFOM system (TIMES) model. The IMRT is a bottom-up energy system model and has been used in studies to examine several combinations of technology and policy options based on constrained optimization in India [55,56]. Detailed technological profiles (plant-level information, fuel characteristics, and processes), cost curves and national and state policies were used to obtain a future profile of fuel-wise installed capacity and electricity generation. For the purpose of this study, data from 2012 were used as a base, and then projections for 2050 were simulated.

3.1.2. Integrated research and action for development

Integrated Research and Action for Development (IRADe) is an independent, advanced research institute, which aims to conduct research and policy analysis for energy, climate change, urban development, poverty, gender equity, agriculture, and food security. The IRADe-IAM model, developed first with the support of the Ministry of Environment and Forest [57], is a multi-sectoral, inter-temporal dynamic optimization model that is bottom-up in the sense that it includes alternative technology options, and top-down in the sense that it covers the whole macro-economy [58–60]. It endogenously solves for major macroeconomic variables, like GDP, sectoral output, consumption, investment, energy demand, energy supply mix and carbon emissions. The IRADe-IAM model forecasts outcomes up to the year 2050 with 25 sectors and 41 production activities. The unique feature of the model is that it projects a changing demand pattern with increasing income levels using nonlinear demand function and changing income distributions for rural and urban areas over a period of 40–50 years [60–62].

3.1.3. The Energy and Resources Institute

The Energy and Resources Institute (TERI) is India's leading think tank dedicated to conducting research in the fields of energy, environment, and sustainable development. The TERI-MARKAL model is a customized version of the MARKAL model for the Indian energy and environmental policy context. The model is based on linear programming optimization and operates in 5 year time periods from 2011 to 2056. The energy system in TERI-MARKAL represents production from coal, natural gas, oil, nuclear, solar, and wind technologies [57,63,64].

3.1.4. Council on Energy, Environment and Water

The Council on Energy, Environment and Water (CEEW) is an independent, not-for-profit policy research institution in India, addressing global challenges through an integrated approach. For this study, CEEW used a customized version of the Global Change Assessment Model (GCAM) Indian Institute of Management Ahmedabad (IIM) version) [65–69]. GCAM-IIM has a focus on India, with assumptions of population, GDP, and electricity-generation technology costs aligned with India-specific information. The GCAM-IIM model also has a detailed building sector module with a focus on urban, rural, and commercial building sectors in India.

3.1.5. Pacific Northwest National Laboratory

Pacific Northwest National Laboratory (PNNL), one of US Department of Energy's national laboratories, uses the GCAM model, an integrated assessment tool for exploring the consequences of climate change [70]. GCAM is a dynamic-recursive model with technology-rich representations of energy production, transformation, and consumption, in each of 32 geopolitical regions where India is a separate region. GCAM operates in 5-year time periods from 2010 to 2100 by solving for the equilibrium prices and quantities of various energy, agricultural, and greenhouse gas markets in each time period and in each of the regions. The energy system in GCAM represents production of coal, natural gas, oil, and uranium along with renewable sources such as solar and wind. GCAM is widely used to analyze energy and climate policies at the national and global levels, including issues concerning water for electricity generation [13,38,41,42,71].

3.2. Population and economic growth assumptions

For consistency, all the modeling teams, except IRADe, used a single set of population and GDP growth assumptions (Table 1). These projections were provided by the National Institution for Transforming India (NITI Aayog). In the IRADe model, GDP is endogenously determined, so IRADe used the growth rate of 6.89% from 2007 to 2030 and 6.57% from 2007 to 2050. The economic growth assumptions are high, much higher than in the Shared Socioeconomic Pathways (SSPs), widely used GDP projections. For example, the SSP2 scenario shows the decline in economic growth rates from 6.9% per year in the 2020s to 3.8% in the 2030s and 2.4% in the 2040s [72]. OECD projections of GDP growth for India [73] are also significantly lower than those provided by NITI Aayog. The population growth trend provided by NITI Aayog is similar to India's scenario in the UN medium variant. All teams used NITI Aayog numbers while IRADe directly used the UN Medium variant population growth figures for India.

3.3. Scenario design

Based on the common assumptions about economic and population growth, four scenarios were produced for each modeling team. These four scenarios entail combinations of greenhouse gas (GHG), cooling technology policies, and water intensities (Table 2). With regards to electricity generation, two projections were produced from each team: a scenario that assumes no new policies in electricity generation; and a low-emission scenario that assumes a 50% reduction in carbon intensity from electricity

Table 1
Population and GDP per capita growth rate, 2010–2050.

Year	Population, NITI Aayog, million people	Population, UN medium variant, million people	Annual GDP growth rate, NITI Aayog, %	Labor productivity growth rate, %
2015	1262	1311	7.8	6.4
2020	1347	1389	8.9	7.5
2025	1425	1462	8.6	7.4
2030	1501	1528	7.3	6.2
2035	1569	1585	7.2	6.3
2040	1632	1634	6.3	5.5
2045	1686	1674	6.2	5.5
2050	1736	1705	5.3	4.7

Source: GDP has been calculated at factor cost at 1999–2000 prices, and provisional value for 2011–2012 was taken from India's Economic Survey. The GDP projection is provided by NITI Aayog. UN population projection are taking from [74].

Table 2
Scenarios for electricity generation and water withdrawals and consumption.

Scenarios	Electricity generation	Cooling technologies	Water intensity
Baseline (BAU)	No GHG policies	Current technology mix	Water consumption and withdrawal with current cooling technology mix
50% emissions intensity reduction (LC)	GHG polices	Current technology mix	Water consumption and withdrawal with current cooling technology mix
Cooling water policies (LW)	No GHG policies	Water-saving technologies	Low water consumption and withdrawal
Combined policies (LCLW)	GHG polices	Water-saving technologies	Low water consumption and withdrawal

generation by 2050 starting in 2018 at the beginning of India's 13th Five-Year Plan.

The teams developed two scenarios for water cooling technologies – a scenario with current cooling technologies and a low-water scenario with water-saving technologies. Cooling technology shares are based on Bhushan et al. [75], Davies et al. [76], and Kyle et al. [38]. The teams assume that the share of cooling technologies and their water intensities remain the same through 2050 in the reference scenario. Indian modeling teams undertook a literature review of recent industry surveys and government reports to ascertain cooling technologies shares and adjusting water coefficients. Data points were scarce and rarely representative [77–80], however, for the purpose of this modeling study, the teams decided to use an estimate provided by a recent independent survey covering about 50% of the current coal thermal power plants [75].

In the low-water scenario, the technologies mix changes after 2020, and by 2030, India phases out once-though cooling systems for inland power plants. This assumption is based on current legislation. The Ministry of Environment, Forest, and Climate Change approved a standard on water consumption limits for coal-fired thermal power plants [81]. The Standards for Water Consumption vide Notification No. S.O. 3305(E) adopted in 2015 require all plants with once-through cooling systems to install cooling towers and achieve a maximum water consumption of 3.5 m^3/MW h by the end of 2017. The standard also expect new plants (to be installed after January 1, 2017) to meet a maximum water consumption of 2.5 m^3/MW h and achieve zero liquid discharge. For this study, it was assumed that after 2030, the share of recirculating technologies will increase to 72% for coal, 82% for fossil non-coal and combined cycle, and 86% for nuclear power plants. Supplement Table S1 shows the shares of cooling technologies in the reference and low-water scenarios. The teams also developed a common set of assumptions about water withdrawals and consumption intensities for cooling technologies (e.g. m^3/MW h). Both water withdrawal and consumption intensities in the reference scenario are adjusted according to Macknick et al. [82], Meldrum et al. [50], and Kyle et al. [38], with the addition of 31% to water consumption for ash handling at coal-fired power plants (the average of those reported by [75,77]).

The teams developed three subsets of water withdrawals and consumption intensities to reflect the substantial uncertainty that exists in the real world regarding these intensities in the Indian power sector. Given this uncertainty, it was valuable to consider how key results would be different under more or less optimistic assumptions about intensities. The minimum intensities are based on Macknick et al. [82], while the maximum ones are taken from Meldrum et al. [50]. The median intensities are from Kyle et al. [38] and Meldrum et al. [50]. This study uses data for a number of fuels and electricity generation technologies. They include coal (conventional pulverized and integrated gasification combined cycle [IGCC]), refined liquids (steam/combustion turbine [CT], IGCC and IGCC with CCS), natural gas (steam/CT, CC [combined cycle] and CC CCS), biomass (conventional, IGCC and IGCC CCS), nuclear (Generation II light-water reactors [Gen II LWR]), hydroelectric, solar (concentrating solar power [CSP], and PV), wind, and geothermal. It should be noted that water withdrawals and consumption intensities are derived from the United States, and they may not accurately reflect the water use for electricity generation in India. For example, Mitra et al. [45] used similar water consumption coefficients for dry cooling of coal and gas power plants. However, water consumption coefficients for wet cooling for coal power plants in that study are in the range of 2.45–3.40 m^3/MW h while this study uses coefficients in the range of 1.24–1.72 for once-through and 3.41–5.45 m^3/MW h for recirculating cooling technologies.

In the reference scenario, water withdrawal and consumption intensities are constant through 2050. In the low-water scenario, water consumption for power plants with water-recirculating technologies is assumed to be 2.5 m^3/MW h or less starting in 2030. Water withdrawals after 2030 are lower proportionally to the decrease in water consumption.

Water withdrawals for recirculating cooling technologies are 30–40 times lower than for once-through technologies. However, switching from once-through to recirculating cooling technologies is associated with higher water consumption. Fig. 1 shows water consumption intensities by cooling technology for traditional fuel use.

In the US, recirculating cooling systems consumed 88% of the water consumed by electricity generation in 2011 (without
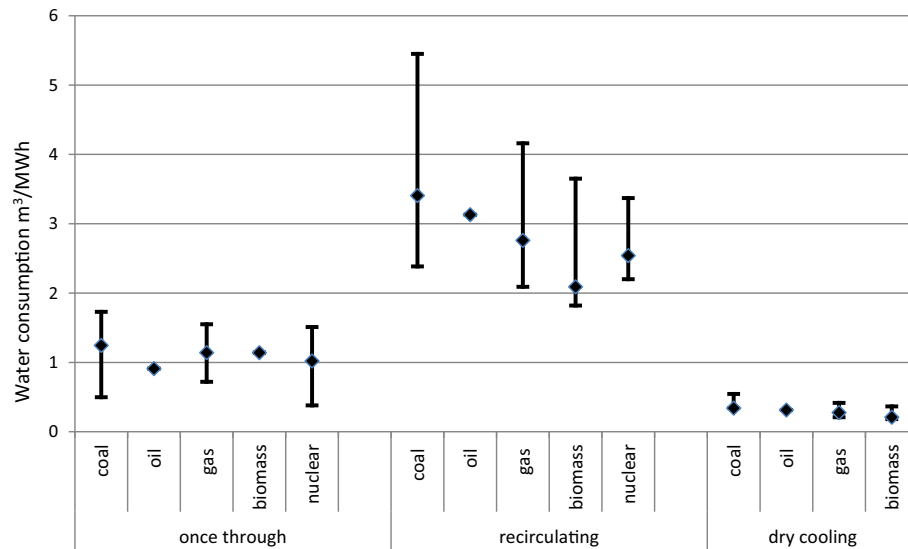
Fig. 1. Median water consumption intensity coefficients by cooling technology and fuel with error bars for minimum and maximum intensities (m³/MW h).

accounting for evaporative losses from hydro) [18]. Supplement Table S2 provides additional details on water withdrawals intensities, and Table S3 shows water consumption coefficients used in this study.

4. Results and discussion

4.1. The evolution of electricity production and emissions

India is increasing electricity production by very impressive rates, with coal playing the most important role. India increased its electricity production from 120 TW h in 1980 to 293 TW h in 1990 and 932 TW h in 2010 [83]. Coal has been playing an increasingly important role in electricity generation: coal power plants produced 51% of India's power in 1980, but their share increased to 65% of electricity generation in 2010 and to 75% in 2014 [83]. India's Central Electricity Authority assessed that the long-term electrical energy requirement could increase to 3710 TW h by the end of the 15th five-year plan (2031–32) [79].

Expectations are that India's electricity demands will continue to grow over the coming decades as the economy grows and more Indians gain access to electricity, and the baseline scenarios support this expectation. Consistent with past trends, therefore, electricity growth rates range from 5.3% to 6.0% per year through mid-century in the reference scenarios, as compared with 7.0% growth over the last several decades. The modeling results show that by 2050, electricity generation in the reference scenario increases more than eightfold from the 2010 level (Fig. 2).

Consistent with this growth in electricity production, electricity emissions grow substantially in the baseline scenarios (without new policies) (Fig. 3). In the baseline scenarios, average emissions across the models increase to 5.6 billion tons (Gt) of CO_2 in 2050. Four teams show CO_2 emission growth by 5–6 times from the level of 2010, while CSTEP projects much higher emission growth. The reason for this high level of CO_2 emissions in the CSTEP model is a very high estimate for electricity generation, with the highest share on coal among all the models (89%) in the no-GHG-policies scenario. The difference in emissions across the models is the result of different overall growth rates in electricity production along with differences in the proportion of electricity produced from different sources. Even with these differences in electricity mix, all models assume that coal is the dominant electricity generation source in all scenarios. In other words, without efforts to

constrain electricity demand growth or alter the energy mix, India's CO_2 emissions will increase dramatically by 2050.

Apart from the broader common insight that coal is going to be the mainstay of the Indian economy under the reference scenario, there are also differences in model results in terms of penetration of other technologies (e.g. solar versus nuclear) with models varying in terms of the future electricity mix as well as the rate of electricity growth. This result is similar to that of other inter-model comparison exercises. Clarke et al. [84], in their comparison of future power-generation mixes across four Asian countries—including India—spanning 21 models, highlight that models differ in terms of how they represent capital stock turnover, rates of technology deployment, base year calibrations shares, regional resources and trade, and differences in technology costs and parameters. Chaturvedi et al. [85] show how differences in base year numbers can lead to significant changes in future numbers even if growth rates are the same. In our study, teams have harmonized the base year GDP and population for year 2010, though one model (IRADe) is based on the social accounting matrix framework, with 2007 as the base year. Future growth of GDP and population has been harmonized to address these variations. However, the model structures are different, and assumptions related to economic and technical characteristics are particularly different across different models, which lead to different technology mixes as well as rates of growth. The variations are in line with the results of other such analysis [84,86]. The results from individual modeling teams represent their outlook of India's future electricity growth and mix, and collectively the results provide a band of uncertainty for deeper insights. This also forms the basis of our estimation of water consumption and withdrawals. Any variation in water-related estimates is entirely due to the underlying variation in electricity growth and mixes because the water coefficients used by all the teams are same.

The application of a carbon-intensity goal reduces electricity emissions relative to the reference scenario and has two effects on overall electricity generation (Supplement Table S4). First, lowering intensity requires a very different electricity mix. All scenarios include a dramatic reduction in the share of coal in electricity generation. What differs in the scenarios is the set of technologies that are used to supplant coal. All scenarios apply some combination of hydroelectric power, solar power, wind, and nuclear, as well as some percentage of electricity generated from natural gas, but the proportions are different. These differences, in turn, lead to
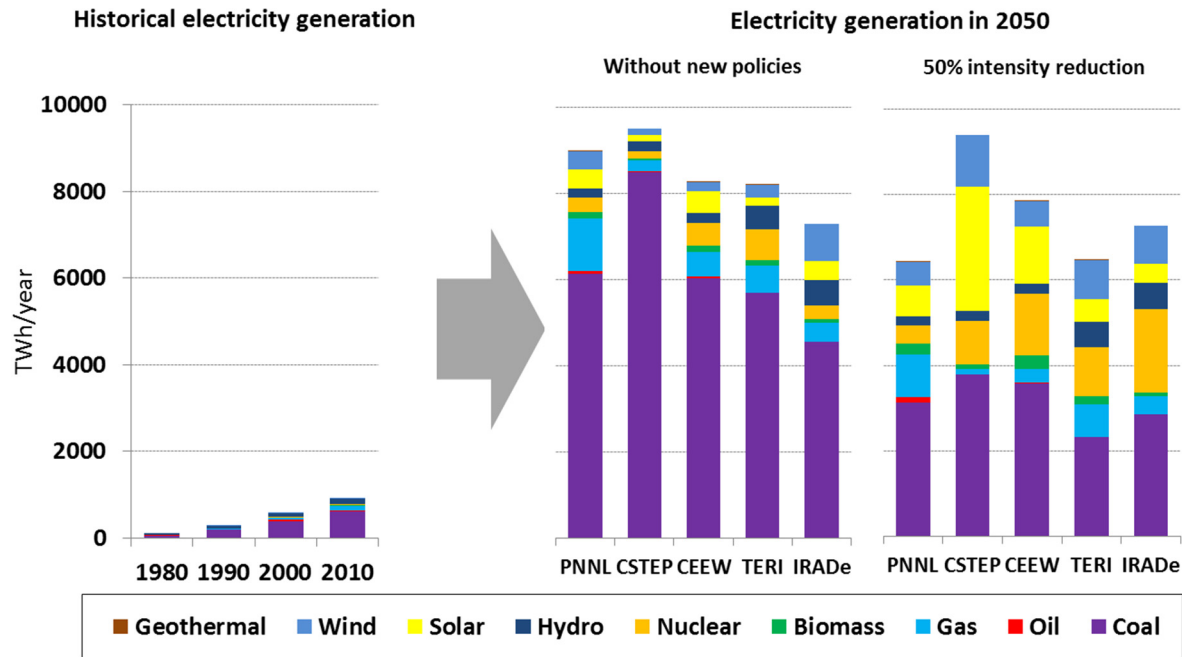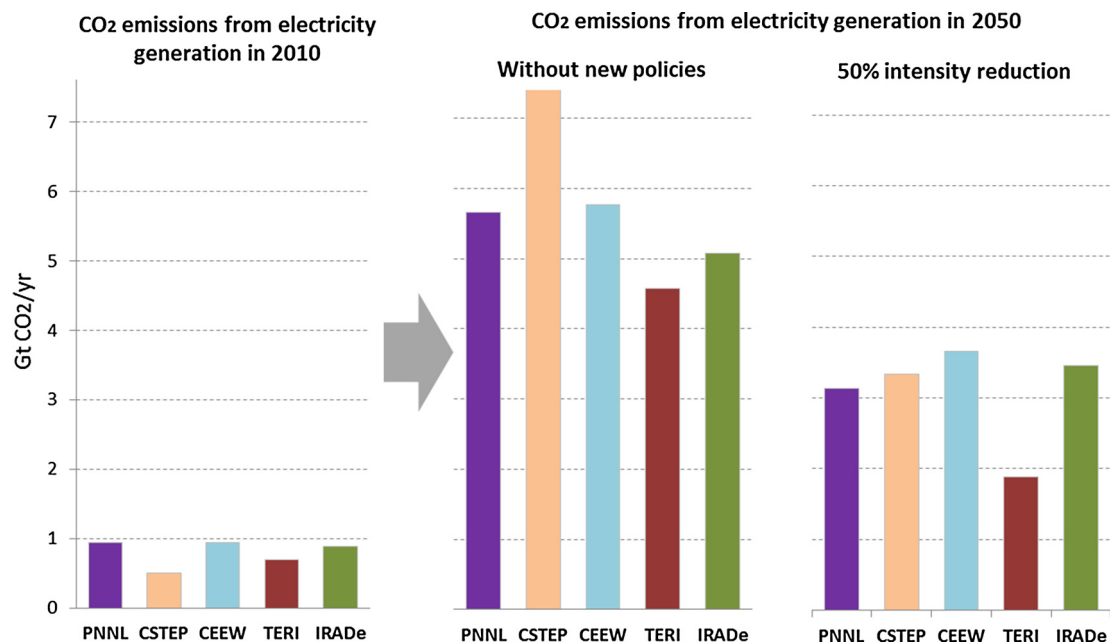
Historical electricity generation

Electricity generation in 2050

Fig. 2. Electricity generation historically and in 2050.

Fig. 3. CO$_2$ emissions from the electricity sector across scenarios.

different water withdrawal and consumption requirements, which will be discussed in the next section. (Note that the modeling teams applied the intensity goal to different levels of precision. The intensity reductions across the teams were as follows: PNNL – 50%, CSTEP – 48%, CEEW – 51%, TERI – 58% and IRADe – 47%).

The second effect of the CO$_2$ intensity policy is some reduction in the growth of electricity generation. The five models used in this exercise show varying levels of response to the carbon policy, which is a result of the different model structures as well as the way the carbon policy is implemented within their respective frameworks. The CSTEP model has very similar overall electricity generation in 2050 for both the reference and policy scenario. This

is because energy demand across end use sectors is entered exogenously in this model, leading to no variation in electricity generation between the scenarios. In the IRADE model as well, there is a negligible decline in total electricity generation even though there is a price response in this model. This is because the cost of nuclear energy is only slightly higher than that of super-critical coal, which it substitutes. As the increase in aggregate price is small, overall demand for electricity also does not decline. The PNNL and TERI models show a significant decline as the electricity price increases due to the policy, and end use demand reduces due to the price effect. In the TERI model, the decline in overall electricity is largely due to increased efficiency of the end use, resulting in lower

electricity requirement. The CEEW model also has price effect inbuilt; however, this model assumes in this exercise that the cost of policy will be mainly borne by the government through a subsidy and not by the consumers. As consumers face only a slight increase in electricity prices, there is a little decline in the electricity generation due to carbon policy.

4.2. Water withdrawals and water consumption for electricity generation

The teams combine two scenarios for electricity generation with two scenarios for cooling technologies and median water intensities and developed four scenarios for future water withdrawals and consumption for electricity generation (see Supplement Tables S5–S8 for detail). These scenarios include the baseline scenario, the low-carbon scenario, the cooling water technologies scenario, and the combined policy scenario.

The teams estimated total water withdrawals and total water consumption at 34 bcm and 4 bcm in 2010, respectively. Coal power plants withdraw the largest share of water while hydro power plants are the largest water consumers (water withdrawals for hydro are not included). Without any water policies (baseline scenario), average water withdrawals are projected to grow ninefold to 224–356 bcm by 2050. Average water consumption increases by fivefold to 18–23 bcm by the mid-century. Water withdrawals grow in line with generation growth, while consumption grows slower than the growth in electricity generation. The changes in the electricity mix from 2010 to 2050 explain the faster grow in water withdrawals: the share of hydro is decreasing (large water consumption without water withdrawal) while shares of coal, nuclear and solar in water withdrawals are projected to increase.

India has developed policies for emission intensity reductions that will impact electricity generation, and the water use will depend on cooling technology choices. The modeling teams projected water withdrawals and consumption in the low-carbon (LC) scenario, which implies the emission intensity reduction of electricity generation by 50% with constant cooling shares and water intensities. In this scenario, average water withdrawals and water consumption are about one fifth lower than those in the reference scenario.

This inter-model comparison allows us to capture variations in model responses across two dimension that affect water withdrawals and consumption: (i) changes in the electricity generation mix, and (ii) reductions in electricity generation because of climate policy. Models vary on both these effects as discussed in Section 4.1. This section highlights the water implications of these effects. First, changes in the electricity mix are an important driver for lower water use. Compared to the baseline scenario, the share of coal in water consumption in the low-carbon scenario decreases twofold while the shares of low-carbon technologies (nuclear and solar) increase by 4–6 times. Though models agree on the significant reduction in coal, there is variation in terms of the extent to which coal is replaced by renewables versus nuclear, which has important implications for water demand. Nuclear energy requires far more water than both solar- and wind-based electricity generation. Second, as compared to other models, PNNL and TERI show a significant decline in electricity generation, which lowers their estimate of water demands compared to other models. The combined impact of the two effects can be seen in the results of the IRADE model, which interestingly show that water withdrawals increase under the low-carbon scenario, contrary to the results of other models. This is because of a high penetration of nuclear energy in this model, which has a higher water withdrawal intensity. Water demand in the future low-carbon world will depend on the extent of the decline in electricity generation and the share of

nuclear versus renewable energy in the electricity mix. This important insight can be derived only through an inter-model comparison exercise.

The modeling results show that the most significant reduction in water withdrawals can be achieved through implementation of water-saving cooling technologies. By phasing out once-through cooling technologies and the reduction of water consumption to 2.5 m³/MW h or less starting in 2030, by mid-century India may reduce average water withdrawals to just 12–18 bcm, or only 5%, relative to the baseline level in 2050. The results show that water consumption in the low-water scenario is very similar to the consumption in the baseline scenario; however, water consumption in the low-water scenario exceeds water withdrawals because of hydroelectric plants that consume about one third of the water for electricity generation without withdrawing it.

The teams also modeled the combined policy scenario that accounts for reduced emission intensity and more effective water use. As in the case of an 'only' carbon policy scenario detailed earlier, model results vary in this 'combined' policy scenario as well. The final result is the net effect of low-carbon policy as well as the water-saving policy. The impact of water-saving policy is same across models as we use exact same share of water cooling technologies and same water coefficients. The impact of climate policy is, however, different across models as explained earlier. In the combined policies scenario, the modeling teams projected water withdrawals at 12–18 bcm in 2050 or only 5% of the baseline level. The combined policies scenario yields similar results for water consumption to those in the low-emission scenario. Looking at the combined impacts, we can robustly conclude that water reducing impacts of water-saving policies far outweigh the impact of climate policy irrespective of the model.

The modeling results show significant changes in the structure in water withdrawals and consumption by fuel in the combined policies scenario. The share of coal in this scenario is lower than in all other scenarios across all models. The analysis found that a strategy focused on renewable electricity from wind and solar PV could substantially reduce water withdrawals in the future. In contrast, a strategy focused more heavily on an expansion of nuclear power would largely continue the growth in electricity sector water demands because nuclear power relies on water-intensive cooling technologies.

These results are consistent with recent assessments of water implications of power generation in the US, China, and the UK [12,30,82,87–89]. The general conclusion is that the retirement of once-through cooling systems and the construction on new facilities with recirculating water technologies can significantly reduce water withdrawals. Macknick et al. [12] also highlights that water consumption can increase in several low-carbon scenarios due to increased deployment of nuclear facilities and coal and gas facilities with CCS. Meanwhile, Wan et al. [89] and Konadu et al. [88] highlight the complementarity of low-carbon options as a strong driver for reducing water consumption and thereby water stress. However, although Wan et al. (2016) highlights the increase in indirect water use in some power-generation technologies and cautions that low-carbon transformation may be constrained in India due to water scarcity for upstream manufacturing, the models in this study have identified like the others that direct water use can be significantly limited with a combination of water use efficiency and renewable energy.

Fig. 4 shows the results of water withdrawals and consumption calculations using median water intensities. The figure shows estimated water withdrawals and consumption by fuel in 2010 in the PNNL model using median water intensities and the range of those for minimum and maximum water intensities (two left bars). It also shows projected water withdrawals and consumption across the models and scenarios from 2010 through 2050.
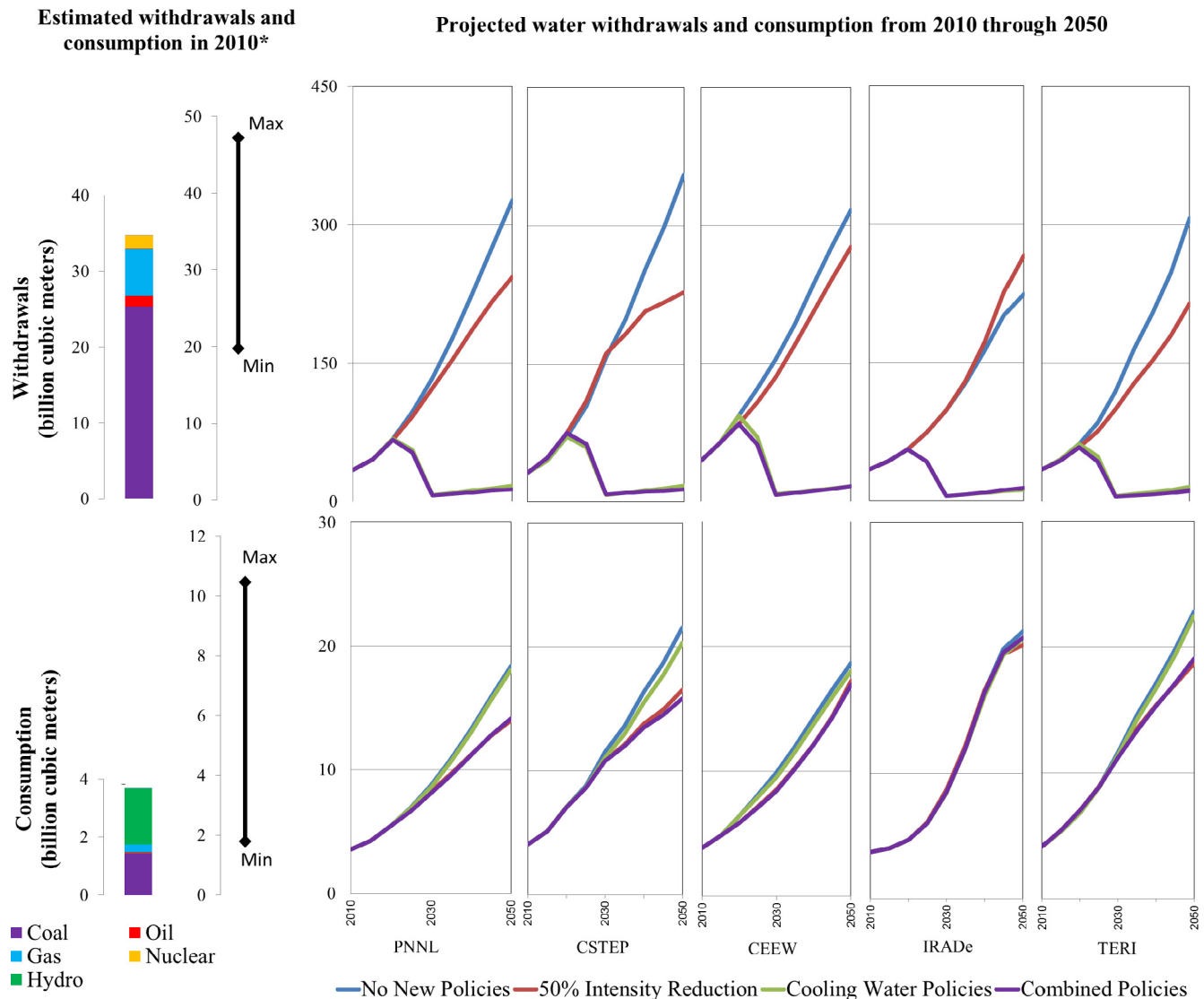
Estimated withdrawals and consumption in 2010*

Projected water withdrawals and consumption from 2010 through 2050

Fig. 4. Projected water withdrawals and consumption across scenarios.

In addition to median water intensities, the teams also projected water withdrawals and consumption with minimum and maximum water intensities. Fig. 5 shows water withdrawals and water consumption in 2050 under four different scenarios with minimum, median, and maximum water withdrawals and water consumption intensities (see Table S9 for detail). Due to uncertainty in the cooling technology shares and water withdrawals and consumption intensities associated with different cooling technologies, there is a substantial uncertainty about current and future water withdrawals and consumption.

Water withdrawals in the reference and emission reduction scenarios calculated with the median intensity are comparable with an estimate from Bhattacharya and Mitra, who projected that electricity in India will require 227 bcm of water in 2050 [46]. However, their underlying assumptions on water coefficients account for both consumptive factors (for recirculating) and withdrawal coefficients (once-through system) in order to estimate overall water requirements.

Shifts to water-efficient cooling technologies reduce the electric-sector water demands, but a high level of policy implementation is key for achieving this reduction. India already has voluntary standards for water efficiency in the power sector, but

implementation has been an issue. There is a risk that even mandatory requirements may not be fully implemented as planned. In addition, power plants have a long life span, which means that India will need to deal with old technologies for a long time. For example, in the United States, the construction of once-though systems peaked in the 1950s, and the country stopped building once-through cooling systems in the 1970s. Still, in 2012, 43% of all cooling systems in the U.S. used once-through technologies. For coal power plants, this share was 52% [90]. In 2011, plants using once-through cooling delivered 23% of electricity in the United States but withdrew 64% of the overall water used by power plants [18].

The teams tested additional scenarios with maximum water withdrawals and consumption intensities and partial implementation of water-saving policies. Under these scenarios, both water-saving policies and switching to closed-cycle cooling technologies are assumed to be implemented in 0, 25%, 50%, 75%, and 100% of cases from 2030 to 2050. Table 3 shows the modeling results of these scenarios.

The results show that, for example, 50% of implementation of water-saving technologies and cooling shares leads to a reduction in water consumption in the range of 7–28% from the baseline
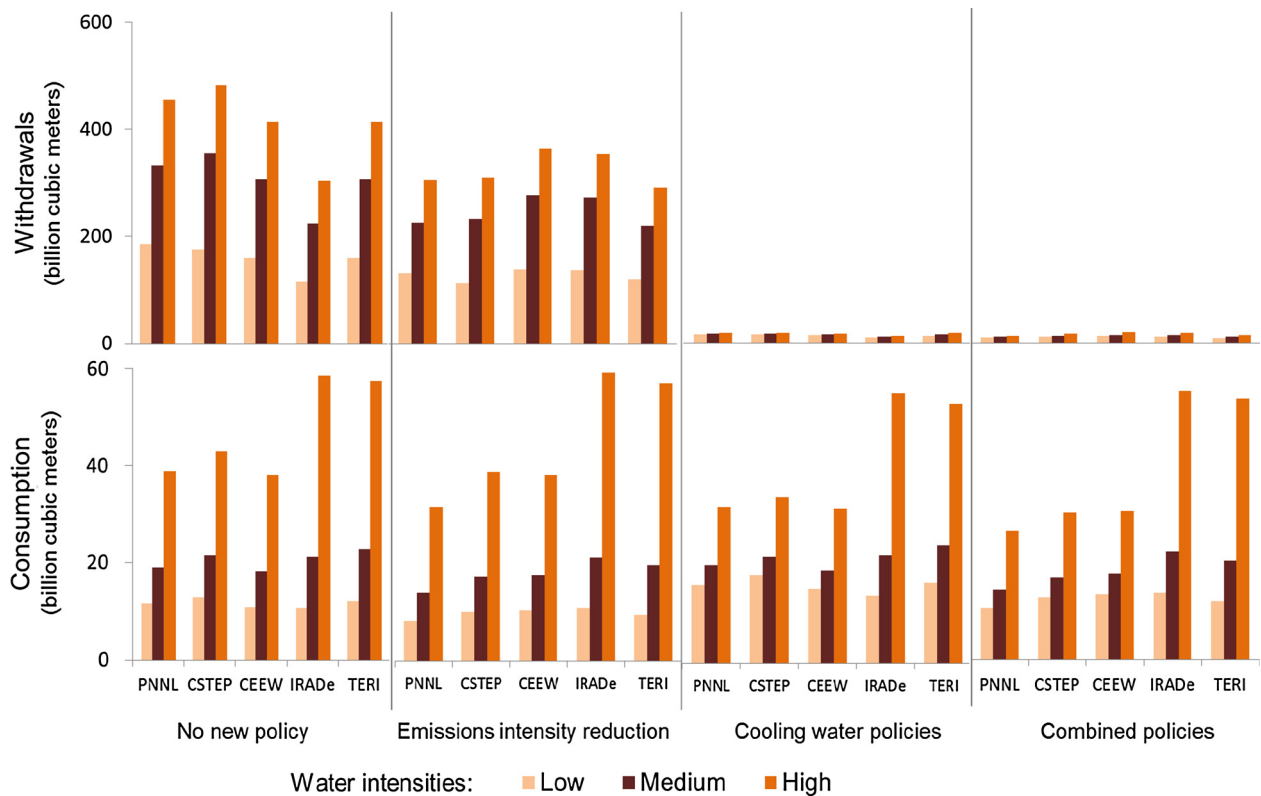
Fig. 5. Water withdrawals and water consumption in 2050 under different scenarios with minimum, median and maximum water withdrawals and water consumption coefficients (bcm/year).

Table 3
Water withdrawals and water consumption in 2050 under the scenarios with maximum water withdrawals and consumption intensities (baseline scenario) and different degrees in implementation of water-saving policies, %.

	Implementation				
	None (Reference)	25%	50%	75%	100%
Withdrawals					
PNNL	100	50	34	19	3
CSTEP	100	48	33	19	4
CEEW	100	66	46	25	5
IRADe	100	87	60	34	7
TERI	100	53	36	20	4
Consumption					
PNNL	100	75	72	68	64
CSTEP	100	82	77	72	66
CEEW	100	92	87	82	75
IRADe	100	95	93	91	88
TERI	100	93	92	90	87

level, while full implementation of the policies decreases water consumption in the range of 12–36%. Water withdrawals under the 50% policy implementation scenario decrease in the range of 40–67%, while full implementation of water-saving technologies and cooling shares decreases water withdrawals by as much as 97% from the baseline level.

5. Conclusions

This paper has explored water withdrawals and water consumption for electricity generation in India through 2050 and effects of water-saving policies on future water demand. India has been increasing electricity production by very impressive rates over the last several decades, and the country's electricity demands

will continue to grow over the coming decades. India already is a water-stressed country, and this rapid increase in electricity generation will require far more cooling water for electricity power plants. An increase in water consumption for electricity generation will limit water availability for agriculture and other sectors of the economy. At the same time, decarbonizing the electricity sector is becoming an important concern.

The unique contribution of this study is that it builds on previous literature by bringing together five modeling teams and coordinating model assumptions. The strength of a multi-model analysis is that it captures model-structure-related uncertainties like response of the system to economic drivers, fuel prices, and climate policies. Each model has its own algorithm and structure representing divergent approaches for modeling the complex

interactions within different components of the system. This multi-model approach provides a means to assess the robustness of key findings, which is not possible in studies from individual modeling teams. The modeling results show that electricity generation in the future depends on India's approach to electricity sector emissions. Without constraining GHG emissions, electricity could increase from 932 TW h to 8500–9500 TW h by 2050 (reference scenario). Electricity generation with GHG policies could be in the range of 6440–9400 TW h or almost 10% lower on average than in the reference scenario.

The research analyzed the role the recent goals in emission intensity reduction, and approved water-saving standards may play a role in future water withdrawals and consumption for electricity generation. The results show that the most significant reduction in water withdrawals can be achieved through implementation of water-saving cooling technologies. Closed-loop cooling technologies can substantially reduce water withdrawals. The results show that water consumption depends on the energy mix and cooling technologies. Decarbonization of the electricity sector serves to improve overall water-savings, though the implications could vary depending on the geographical region. Focusing on wind and solar power reduces consumption, while a focus on hydroelectric power increases water evaporative consumption. The application of closed-loop cooling technologies increases water consumption compared to once-through cooling technologies. Water-saving technologies, like solar PV, can offset the increase in possible water withdrawals and consumption.

The results of this study can be used by the Indian government for better water management and strategic planning. The modeling results show future water needs for electricity generation so that the government can choose to proceed with additional measures to reduce water withdrawals in the future. For example, the government can speed up phasing out once-through technologies in most water-stressed regions to reduce water withdrawals once a spatial analysis has been undertaken. Water-recirculating technologies, however, increase water consumption. If the strategic goal is to reduce both water withdrawals and consumption, the government should promote dry cooling as well as wind and solar PV. The assessment of water needs for electricity generation helps understand an important component of future water demand.

This study reveals some important gaps in our knowledge about the water-energy nexus in India. First, in absence of India-specific water withdrawal and consumption coefficients, we use global median values. There is a need to establish country-specific water withdrawals and consumption intensity coefficients. India-specific water consumption will provide better estimates. Hence, it is important to collect this information for future studies. Second, better understanding of the cooling technologies of India's thermal power plants is needed for a more accurate assessment of water use for electricity. Third, there is a need for more detailed regional assessment of water use in the most water-stressed areas, for example in northern and northwestern India. Finally, there is an urgent need to create a detailed water demand and supply model to analyze water use in the country as a whole, as well as in most water-stressed regions. These questions are subjects for future research.

Acknowledgment

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.04.079.

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